REMOTE GEOCHEMICAL SENSING OF ASTEROIDS

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The techniques of remote geochemical sensing are substantially the same for any planetary body without an atmosphere, or with an atmospheric column density of less than about 10^{-3} g/cm^2 surface. Thus the paper by Haines *et al.* (1976) provides a proper and current technical basis for the present subject. A few new points will be noted below after a quotation of the abstract from Haines *et al.* (1976).

> Two instruments, the gamma-ray spectrometer and the x-ray fluorescence spectrometer, are uniquely suited to the chemical mapping of planetary surfaces from orbit. Through their detection of characteristic line spectra they measure the concentrations of a suite of elements in each area overflown. Multi-element chemical maps derived from these remote measurements are used in the construction of evolutionary models of planetary bodies and of the solar system as a whole. The NaI(Tl) gamma-ray spectrometer and a gas proportional x-ray spectrometer were flown over 20% of the lunar surface during the Apollo 15 and 16 missions. These instruments measured chemical differences across the boundaries of known lunar provinces and revealed several new features of lunar-surface composition. Advanced spectrometers which are under development for future missions are able to educe much more information in a given time span than the Apollo instruments. They may be used in possible future missions such as Lunar Polar Orbiter, a Mars orbiter, a Mercury orbiter, outer planet satellite missions, rendezvous with asteroids and cometary nuclei, and surface-penetrating planetary probes.

In essence, using the gamma-ray and x-ray techniques together, all major elements, the radioactive elements Th, U, and K, and certain trace elements, especially H, can be analyzed with good sensitivity and reasonable accuracy. This is a sufficient data set for most (but not all) investigations in geochemistry and planetary evolution. For asteroids there are two possible mission modes.

The largest objects, of diameter hundreds of kilometers, appear to be at least rather closely spherical. Their gravitational acceleration is such that injection and maintenance in orbit seems practicable (to a chemist). It also seems worthwhile. Although there are as yet no positive indications of regional differences of composition, our knowledge of the Moon, and of the variations in visible and IR spectra among asteroids, suggests that this is likely.

The smaller asteroids, below some size limit, will not be so easy to orbit. Perhaps they will also be more homogeneous in composition. However, if they are fragments of larger bodies, they may allow us to sample a vertical profile of differentiation. This would be very exciting. Technically, the operations people will have to tell us how to "station-keep" around different parts of the surface, to get the necessary geochemical and geophysical data.

The current experimental technique for gamma-ray spectrometry follows closely that described in Haines *et al.* (1976). Abundances appropriate to less differentiated bodies--closer to or identical with chondritic patterns--would modify their Table 1, which is reproduced here, but yield no surprises. At greater distances from the Sun the cooling of the Ge detector becomes easier. The one new development is the demorstration by Haines and Metzger (1978), using Apollo gamma-ray data, that deconvolution of instrument areal response, to get closer to the true source map, can be made practical. If this can be done with these comparatively noisy, low-resolution data, we should be able to do much better in any future mission. Thus the limitation of areal resolution to a value close to the altitude of the spacecraft above the surface can be removed. Resolutions as good as one-third or one-fourth of the altitude may be attainable, for sharply contrasting chemical provinces.

Table 1. Calculated Lunar Sensitivity Limits with 80-cm^3 Germanium Detector at 100-km Altitude*

Element	Observing Time			Lunar Soil Types		
	1 hr 3σMDL	10 hr 3σMDL	100 hr 3σMDL	Highland (A-16)	KREEP (A-14)	Mare (A-11)
Th ppm	0.52	0.17	0.052	2.11	14.0	2.1
U ppm	0.12	0.039	0.012	0.58	4.0	0.55
K %	0.028	0.0087	0.0028	0.096	0.430	0.115
Fe %	2.2	0.70	0.22	4.0	8.0	12.3
Ti %	0.90	0.23	0.090	0.34	1.0	4.6
Si %	3.4	1.1	0.34	21.1	22.5	20.C
O %	6.5	2.1	0.65	45.0	44.2	41.6
Al %	5.5	1.8	0.55	14.4	9.2	7.10
Mg %	3.0	0.95	0.30	3.3	5.60	4.60
Ca %	20	6.2	2.0	11.2	7.60	8.60
C %	5.4	1.7	0.54	-	-	-
H %	0.75	0.24	0.075	0.0015	0.004	0.007
Na %	1.0	0.32	0.10	0.350	0.470	0.32
Mn %	1.8	0.56	0.18	0.054	0.100	0.1C
Ni %	1.2	0.38	0.12	0.045	0.040	0.024
Cr %	4.1	1.3	0.41	0.075	0.13	0.195
S %	7.3	2.3	0.73	0.060	0.10	0.10
Cl %	0.26	0.081	C.026	0.0012	0.010	0.003
Lu ppm	11	3.5	1.1	0.5	3.2	1.6
Gd ppm	250	80	25	7	35	17

*Haines *et al.* (1976).

For x-ray spectrometry, proportional counters still appear best, although the other detectors mentioned have not been ruled out. An improved solar monitor, using a glass test panel of known composition, inserted periodically into the field-of-view, should markedly improve precision and ease of interpretation. The resolution element on the surface can be narrowed, as in the Apollo experiments, by passive shielding. The lower flux of solar x-rays found in the asteroid belt will slow up the gathering of statistics, but not in a troublesome way.

A critical fact about the gamma-ray system is that its sampling depth is on the order of tens of grams per cm^2, or tens of centimeters at low density. It is important to establish, if possible, the mean thickness of the regolith on target objects, and the fraction of "bare" area on this scale. There are plausible arguments that the smaller target objects, at least, should have regoliths thinner than this, and perhaps considerable areas with no visible covering. We cannot yet be certain.

It seems to be agreed at this meeting that multiple-target missions are to be preferred. This is certainly true from the geochemical point of view. It is also important that other observations require (or prefer) substantial stay times at each object. This is important for gamma-ray spectrometry--much less so for x-ray analysis.

REFERENCES

Haines, E. L., and Metzger, A. E. (1978). High resolution thorium maps by means of spatial deconvolution as applied to the Aristarchus plateau (abstract). *Lunar Science IX*. In press.

Haines, E. L., Arnold, J. R., and Metzger, A. E. (1976). Chemical mapping of planetary surfaces. *IEEE Trans. on Geosci. Electron.* GE-14, 141-153.

DISCUSSION

ECONOMOU: Can you describe the sensitivity and measurement accuracy of the gamma-ray technique for various elements?

ARNOLD: For all the major elements listed in Table 1 and for long stay times, the sensitivities are certainly better than 1% of that element--it differs from element to element depending on the detection limit. I think there will be an improvement in accuracy with the germanium system. If we normalize to an element like silicon or oxygen, the accuracy for the elements that are well-determined is certainly on the order of 5% relative or somewhat better. For asteroids that are irregular in shape, the geometrical corrections are difficult, so placing everything on an absolute basis may be a little tricky. But if we normalize to a major element and note that everything has to sum to 100%, then I think we can get an iron-to-silicon ratio and similar ratios to better than 5%.

ECONOMOU: Do you require ground truth to normalize your results?

ARNOLD: Well, ground truth is always very desirable. The normalization question has to be answered differently for radioactive elements than for the major elements. In the case of the radioactive elements the decay constants are very well known. Thus, one can just normalize them as closely as one pleases without ground truth. In the case of the other elements there are nuclear physical parameters, cross sections, which can be uncertain by 10-15% in the best measurements. I don't know if they will be determined better than that by the time this mission flies. In the case of the Moon we have applied ground truth factors in order to obtain more reliable analytical results. Why not use the Moon as ground truth because we have flown the Apollo mission? You can do that, but we used what is by present day standards a rather inferior instrument, so that correction might not be good enough. For some elements where you have both the x-ray and gamma-ray methods, you can compare one to the other. Were we lucky enough to get a gamma-ray spectrum from orbit and to have an alpha experiment on the ground, such a comparison, I think, would be fruitful for both. So the question of normalization does introduce some potential problems among the major elements. But I think these are the different ways of attacking it.

FANALE: The solar-induced x-ray flux is lower in the asteroid belt. Does this cause problems for the x-ray system?

ARNOLD: The counting limitations of the x-ray system are much less than those of the gamma-ray system. Both can use all the time we can get. I am terribly glad to have optical people say they want to be around for a long time, to take some of the pressure off of us. The unit of x-ray data which was processed on the Moon is e[illegible]

8 or 16 sec. Multiply that by nine, to account for the decrease in solar flux at 3 AU, and you still have plenty of time to collect the desired data. Having both gamma-ray and x-ray experiments is useful for cross-checking and for improving the aerial resolution by passive shielding of the x-ray detectors and for the possibility of comparing the mean composition over a 30 cm depth, to that over a fraction of a millimeter.

FANALE: Would you say something about carbon and hydrogen?

ARNOLD: A very good point. Because people are much more aware of the lunar work we've done, the sensitivity to carbon and hydrogen is perhaps not well known. The sensitivity to hydrogen is enormous for gamma-ray techniques, easily 0.1%. One sees hydrogen in two ways, as a neutron capture line, and it changes the neutron spectrum in a radical way. If you had 1% water of hydration, if you had a rock as wet as the typical crustal basalt or granite on the Earth, then you would have qualitative changes in the ratios and intensities of certain lines. This also extends the depth range. One is really looking down a couple of meters, because the neutron economy is the thing that determines it. We are about as sensitive to carbon as we are to most other elements. There is a 4.4 MeV line. I would say the sensitivity is a percent or a fraction of a percent. The amount of carbon found in the C1 or C2 meteorites would be no problem.

McCORD: This is a case where two techniques, the optical and the higher energy techniques, complement each other. Carbon and opaques, for example, are materials we have difficulty distinguishing optically. Measuring them like this we can very quickly eliminate ambiguities.

CHAPMAN: For the small irregular asteroids you are limited in your resolution to something like a tenth of a radius simply by the necessity of being far enough away that you are not hit by a mountain. That resolution nevertheless seems good to me.

ARNOLD: For a larger object like Ceres or Vesta, we would certainly want to map from orbit. That is the way to get the ultimate aerial resolution and to work together with the other techniques. For the smaller ones, if you are doing station-keeping, I think you would want to concentrate on particular interesting features.

NIEHOFF: I would like to comment that the way in which one generates coverage, even though you are orbiting, is not in the traditional sense you think of for LPO, for example. The asteroids are spinning more rapidly than your orbit period, so you essentially peel them like an apple. The same thing happens at a smaller object in the station keeping mode. That is, the object won't hold still for you unless you go into a synchronous orbit about it so you can do long duration observations of specific spots.